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(Principal Investigator: E. H. Timothy Whitten)

NORTHWESTERN UNIVERSITY REPORT NUMBER 24

FINAL REPORT

by

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with assistance of

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Statistical evaluation of the composition, physical properties, and surface configuration of terrestrial test sites and their correlation with remotely-sensed data

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October 7, 1970

This research grant was initiated on August 1, 1964 and was funded through July 31, 1968 as follows:

	per annum	total
August 1, 1964 - July 31, 1965	$21,469.25	$ 21,469.25
August 1, 1965 - July 31, 1968	$41,748.00	$125,244.00
Total Grant		$146,713.25

However, the grant was extended through July 31, 1970 without additional funding.

A wide spectrum of research problems has been tackled under the general heading of statistical evaluation of the composition, physical properties, and surface configuration of terrestrial test sites and their correlation with remotely-sensed data. Results have been incorporated in twenty-four reports; the 23 Northwestern Reports and the one NASA Contractor's Report are listed in Table 1. In addition, a large number of ideas generated in the course of this research program have been incorporated in the scientific journal literature; specifically, this has been the case with the five articles listed in Table 2.

In a continuing effort to understand the nature of the spatial variability of scalar and direction attributes of materials at the lithosphere-atmosphere interface, a wide range of statistical techniques has been analyzed in depth. Included were:

Table 1 - reports issued under research grant

N. U. Report	Title	MSC Data Bank #	STAR #
1	Interim progress report 3-31-65	NR-E6-EJ-002-00065	-
2	Semi-annual status report 9-30-65		
3	Semi-annual status report 3-31-66	NR-E6-EJ-998-00020	X66-18322
4	Aspects of geological sampling at test sites	NR-E9-00-000-00011	X66-21277
5	Preliminary details of sampling locations at NASA Sonora Pass Test Site, California	NR-E8-EJ-019-00010	X66-21280
6	Semi-annual status report 9-30-66	NR-E6-EJ-998-00030	-
7	Statistical problems involved in remote-sensing of the geology of the lithosphere-atmosphere interface	NR-09-00-000-00035	
8	The general linear equation in prediction of gold content in Witwatersrand rocks, South Africa	NR-09-00-000-00036	
9	Semi-annual status report 3-31-67	NR-E6-EJ-998-00035	N66-81471
10	FORTRAN IV programs to determine surface roughness in topography for the CDC 3400 Computer	NR-09-00-000-00284	
11	A program for the rapid screening of multivariate data from the earth sciences and remote sensing	NR-09-00-000-00052	
12	Two programs for the factor analysis of geologic data	NR-E9-EJ-019-00067	N67-39920
13	The geology of the lower Precambrian rocks of the Champion-Republic area of Upper Michigan (NASA Test Site 126)	NR-E9-GK-126-00068	N67-39848

Table 1 (Cont'd.)

14	The geochemistry of the Fremont Lake quartz monzonites and associated gruss, NASA Sonora Pass Geologic Test, Sierra Nevada, California	NR-E9-EJ-019-00073	N68-10180*CSCL*08D
15	Semi-annual status report	NR-E9-EJ-998-00745	X68-16119
16	Variance of some selected attributes in granitic rocks	NR-E9-00-000-00181 (NASA-CR-101747)	N69-30686*#CFSTICL08G
17	FORTRAN IV CDC 6400 program to analyze subsurface fold geometry	NR-E8-00-000-00080	N69-13568
18	Semi-annual status report 9-30-68	NR-E9-GK-126-00746	X69-10963
19	NASA Geological Test Site #126 Marquette-Republic Trough, Michigan: Report on photographic imagery obtained on Mission 72, May, 1968	NR-E6-GK-126-00078	N69-12097*#CFSTICSCL08G
20	Relict diagenetic textures and structures in regional metamorphic rocks, Northern Michigan (NASA Geological Test Site #126)	NR-E9-GK-126-00671	-
21	A FORTRAN IV program for two-dimensional autocorrelation analysis of geologic and remotely-sensed data	NR-E9-00-000-00908	-
22	A sequential linear discriminant analysis program for geological and remotely-sensed data	NR-E9-00-000-01128	-
23	Enigmas in assessing the composition of a rock unit: a case history based on the Malsburg Granite, SW Germany		

NASA Contractor's Report	Title
CR-318	A surface-fitting program for areally-distributed data from the earth sciences and remote sensing by Whitten, E. H. T., Krumbein, W. C., and Beckman, W. A., Jr., pp. 1-146.

Table 2 - Journal articles in which acknowledgement of NASA Research Grant Funds made

1967 - Whitten: Fourier trend-surface analysis in the geometrical analysis of subsurface folds of the Michigan Basin: Kansas Geol. Survey Computer Contrib. no. 12, pp. 10-11.

1969 - Whitten and Beckman: Fold geometry within part of the Michigan Basin, Michigan, USA: Amer. Assoc. Petrol. Geol. Bull., v. 53 pp. 1043-57.

1969 - Whitten and Beckman: Three-dimensional variability of fold geometry in the Michigan Basin: Geol. Soc. Amer. Bull., v. 80, pp. 1629-34.

1969 - Whitten: Trends in computer applications in structural geology: in 'Computer applications in the earth sciences' Edit. D. M. Merriam, Plenum Press, New York, pp. 223-49.

1970 - Whitten: Orthogonal polynomial trend surfaces for irregularly-spaced data: Internat. Assoc. Math. Geol. Bull., v. 2, pp. 141-52.

Polynomial surface fitting: both nonorthogonal and orthogonal polynomial methods for irregularly-distributed data points.

Double-Fourier-Series surface fitting for irregularly-distributed data.

Two-dimensional autocorrelation analysis.

Vegetation-density analysis.

Nature and variability of surface roughness in topography.

Description and mapping of fold geometry in terms of scalar variables.

Development of computer programs for (a) rapid screening of multivariate data, (b) factor analysis, and (c) sequential linear discriminant analyses.

In the last few months, particular attention has been paid to spline functions and spatial-filtering techniques; additional work on these methods is planned after conclusion of the present research grant.

These and other statistical methods were used extensively in assessing the nature and variability of significant geological-test-site variables; this has provided considerable insight into the complex nature of ground truth and the intense complexity of the lithosphere-atmosphere interface that is or would be scanned by a remote sensor. At an early stage it became only too clear that such apparently-simple geological sites as Pisgah Craters and Sonora Pass are intensely complex in terms of the sequential images 'seen' by a sensor. In our first report (1965, p. 7), it was stated that:

> "In general, it would seem that the severe statistical problems involved in establishing ground truth on the basis of any form of remote sensing force the conclusion that at least one very simple test site should be studied. Sampling at Pisgah has already demonstrated that the area is extraordinarily heterogeneous and statistically complex . . ."

In Report 3 (1966, p. 3) we wrote:

"We have repeatedly emphasized that remote sensing of geological ground truth must be tackled as a multivariate statistical problem and that the main hope of interpreting the atmosphere-lithosphere interface by remote sensing is likely to come from obtaining digitized data from numerous sensors - for "calibration" purposes it is essential that the several sensors "look" at <u>identical</u> targets."

In June 1966 (N. U. Report 6, p. A-1) we had to report that we had been unable to acquire any remote sensor data and in March 1967 (N. U. Report 9, p. 3) that:

"We were expressly requested not to become involved in developing remote-sensors, and not to overlap the work of other teams charged with compiling the "ground-truth" of the several NASA geological test sites. However, because of the continuing general lack of both remote-sensor data and related ground truth, the Northwestern group has had to generate raw data with which to test statistical models."

Later (N. U. Report 15, May 1968, p. 6) it was reported that:

". . . the magnitude and importance of the sampling and statistical problems have continued to be underestimated or ignored by most of the scientists working with the development of remote-sensing instruments. In our previous reports, it has been repeatedly emphasized that, before any significant use of remotely-sensed data can be anticipated in the earth sciences, these sampling and statistical problems must be thoroughly evaluated. A whole multitude of complex questions is involved.

"The following remarks of Simonett (1966, p. 2) are wholly applicable to geology and to all the earth sciences:

"The most pressing present need in remote sensing in geography is not the immediate development of newer, fancier remote sensing devices. The fundamental problem remains that of learning how to interpret and evaluate the information contained in different parts of the electromagnetic spectrum using existing sensors."

In collaboration with the University of Nevada Team, we organized a project in July 1967 to analyze a large volume of microwave data obtained by the NASA aircraft for the Sonora Pass geological test site, California. We set up the ground truth requirements for a statistical analysis but, unfortunately, due to pressure of work at other test sites, the Nevada team has not yet been able to generate the required ground-truth-data matrix, although most (if not all) of the necessary field data were collected in 1966. The exacting ground truth requirements were set out in Appendix A of N.U. Report 15 and would serve as a guide for any realistic remote-sensing effort. The Sonora microwave and ground truth data appeared to be the most promising for a practical test of theoretical statistical models that we had been developing over the previous years.

Because of the obvious potential and importance of structural analysis based on radar imagery, the Northwestern team initiated work in the Marquette-Republic Trough, Upper Michigan - an area of great economic and structural interest. The main hope was to compare structures mapped on the ground with those seen in radar imagery. Despite repeated, determined efforts on the part of the Northwestern University team, radar imagery has still not been provided by the NASA aircraft, although photographic imagery was <u>eventually</u> supplied to us and reported upon in our reports.

On June 7, 1968, Dr. John Porter (NASA HQ, Washington, D.C.) suggested that the Northwestern University team should evaluate the current status of the whole NASA remote-sensing program as applied to the geological sciences - particularly as assessed in the light of our contribution to NASA objectives over the previous few years. After reviewing statements made by us (a) at numerous NASA-sponsored test-site conferences and (b) in Northwestern University Reports (see Table 1), it was difficult to do anything but reiterate the same basic points. The conclusions developed at that time (N.U. Report 18, pp. 4-9) are restated here, as they still reflect a summary and synthesis of our experience and position. The points raised should, in our view, be considered carefully before planning <u>any</u> new remote-sensing efforts.

"There are several totally dissimilar approaches to the remote-sensing program: three may be summarized as follows.

1. <u>Empirical approach involving multivariate statistical analysis of carefully collected, but currently unavailable, data</u>.

"Our basic philosophy has been and still is that, if any significant success is to be made with remote sensing for geological purposes, the whole subject must be treated initially as a multivariate statistical problem. In practice, each sensor (using a small part of the total electro-magnetic spectrum) measures hundreds of attributes (e.g., one attribute would be the amount of energy of a specified wave length emitted). The sole reason for the remote-sensing research program is that we do not know which single attributes or which combinations from amongst the thousands of attributes that could be measured, permit accurate predictions to be made about the nature of a particular sensed target.

"Similarly, each narrowly-defined geographic domain (or sensed target) can be described accurately in terms of thousands of quantitative and qualitative variables. Although scientific and/or intuitive judgments can be made about which of these variables are most likely to be significant for sensing experiments, it remains that one does not know positively which "ground truth" attributes control the observed remotely-sensed data. It is not known how to measure many (possibly most) properties of "ground truth" and very little is known about the several levels of variance of each variable involved.

"Various standard statistical techniques are available that would readily permit the significant sensed variables to be identified and correlated with meaningful attributes of the sensed target. However, to implement a program to do this would involve extensive experiment. Unfortunately, in order to determine how to sample, it is almost always necessary to conduct a preliminary sampling program to discover the "behavior" of the variables of interest.

"In the present context, implementation of a successful remote-sensing program has three basic requirements. Over the past four years, we have restated these many times but, to date, essentially no attempt has been made to include them in ongoing plans. Until such time as they are incorporated in some basic NASA programs, it seems that the remote-sensing program will achieve, at best, limited success. The requirements are:

(a) Conduct at least one (preferably more) experiment on a geologically very simple, small geographic area; although chosen as being geologically-simple test sites, places such as the Pisgah Craters and Sonora Pass Test Sites, California are horrendously complex. At an early stage in the program, we repeatedly advised capitalizing on the knowledge gained from Pisgah Craters, but to abandon the site in favor of a much more simple location. However, in fact dozens of <u>much</u> more complex geological test sites have been incorporated in the NASA program and almost all have received less rigorous study than the original Pisgah site.

(b) Use as many sensors as possible, retain the original raw data for each smallest possible sector of the electro-magnetic spectrum, and insure that each sensor concomitantly sense <u>precisely</u> the same area on the ground for each integration time of the several experiments; initially, this might involve use of helicopters rather than aircraft for carrying the sensors. Because of the immense variability of terrestrial terrain, initial experiments conducted in any other manner will automatically introduce complexities that it is probably impossible to screen out. The geological remote-sensing program is an exciting long-term research problem, but some of the necessary basic research could readily be done now (and could have been done during the past four years). However, currently, data do not exist that would allow even a pilot study to be conducted along the lines indicated.

(c) Obtain digitized data from sensors; photographic-type data can theoretically be reduced to digital form but the process introduces an additional complexity that can only hinder the first realistic statistical analyses.

2. <u>Theoretical approach through simulation studies that would permit (a) mathematical models to be generated to predict interaction and responses and (b) comparison of actual remote-sensing experimental results with predictions to provide a basis for checking, modifying and finally adopting a particular model</u>.

"With increasing use of computers in the geological sciences, considerable interest has developed in simulation studies during the past two or three years. Several elementary computer-based simulation studies (<u>e.g.</u>, basin sedimentation models) have yielded considerable insight into the actual geological processes that have occurred in nature. Simulation could also play an important role in a complete remote-sensing program for terrestrial resources. It is of great interest that Dr. Larsen of the NASA Electronics Research Laboratory, Cambridge, is actively fostering simulation studies of the atmosphere and hydrosphere in order to develop understanding of electro-magnetic responses during sensing experiments. A program devoted to simulation of the atmosphere-lithosphere interfacial zone and to its interaction with electro-magnetic waves would be a long-term project invaluable to the terrestrial-resources program.

3. <u>Continue to develop independently a lot of tools and apparatus, continue to test these independently, and hope that qualitative and semi-quantitative appraisal of the results will permit worthwhile conclusions to materialize</u>.

"The individual experiments may be the best possible but, if developed in this context, much of their inherent value would or could be lost[1]. For the past 100 years geology has advanced in this manner -- a manner that can be, not inappropriately, compared with Victorian natural historianism -- but, over the past decade, geology has steadily begun to be transformed into a rigorous scientific discipline that is subject to quantitative and qualitative testing.

"Basically, and again we reiterate, the fundamental problem concerns unequivocal definition of objective. The point will be re-made by analogy with some geological "research." In the past many a student has gone out into a new area, worked vigorously, and collected all sorts of information about, say, mineralogy, fossil echinoids, eskers, Precambrian amphibolites, imbricate pebbles, etc. within his area. After an exhausting summer, he has returned to the laboratory to "shake" and "massage" his data in the earnest hope that some valuable results, conclusions, and a Ph.D. thesis will filter out. If something falls out, it clearly defines the objective! Alternatively, and more realistically, a clearly-defined objective is developed at the outset of the research (in terms of clear unequivocal operational definitions), and solutions to the scientifically-stated problems are obtained.

"Again reiterating, it seems to us that the short-term and long-term objectives of the terrestrial resources remote-sensing

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[1]This generalization has been deliberately somewhat overstated. It is recognized clearly that some sensors (<u>e.g.</u>, some side-looking radars) already have tremendous demonstrated potential in their own right. Nevertheless, even for such sensors, it is maintained that the claims in this paragraph are valid.

program require clear and unambiguous definition; as experience is gained, the objectives may require some minor modification. With such definition, the resources available could be specifically oriented towards the goal. Without such objectives, technical resource use cannot be optimized and it would only be by "shaking" the assembled haphazard results that the economically-significant "prize" <u>might</u> fall out.

<u>Summary</u>:

"Thus, the definition of objectives is long-overdue. The long-term approach should aim at the simulation approach to insure an adequate understanding of the physical principles involved. Of immediate importance would be implementation of a program to capitalize on the empirical approach; such an approach could be expected to secure usable results in a relatively short time provided that the three points (a, b, and c) referred to above are included as an integral part of the program. It is believed that definition of the objectives for the terrestrial resources remote-sensing program will necessarily involve incorporation of these three points (despite the fact that, for convenience, everyone has studiously avoided recognizing them <u>in fact</u> over the past four years)."

CONTINUING WORK ON AREALLY-DISTRIBUTED DATA

by Walter A. Beckman and E. H. Timothy Whitten

At this time of termination of the NASA Research Grant, a study is underway utilizing spatial-filtering methodology for analyzing the structural configuration of the top of the Dundee Limestone in a part of the Michigan Basin. Previous structural analyses of this surface have been made by Whitten and Beckman (1969) and Beckman and Whitten (1969) using polynomial and, for the most part, Double-Fourier-Series trend surfaces. This study was initiated, in effect, to compare the merits of three types of mathematical models for analyzing the same areally-distributed data. A considerable expenditure of time was required at the start to comprehend the spatial filtering procedures described by Robinson (1968, 1969, 1970); Robinson, Charlesworth, and Kanasewich (1968); Robinson and Charlesworth (1969); and Robinson, Charlesworth, and Ellis (1969).

It must be pointed out that there is a primary difference in the three numerical procedures. Polynomial and Fourier Series methods are designed for fitting the "best" mathematical surface to the available data and an operational decision must be made as to the order surface which best expresses the existing trend (Chayes, 1970). The residual values indicate the deviations of the data from the computed surface. Spatial filtering of data is carried out to emphasize features having a particular range of wavelengths while suppressing all others in an area. From an estimate of amplitudes of existing spatial frequencies, the operator generates a filter which isolates the structures having dimensions considered to be significant to the particular study. With a properly-designed filter, the average elevation of the map area is eliminated from the filtered output.

The problem inherent in the use of spatial filtering is the necessity of working with gridded data (Whitten, 1969). It was evident from our previous work that use of manual contours as a basis for interpolation can impart a significant operator bias to the subsequent mathematical model. In order to determine visually the effect of this bias in the maps generated by each of the numerical methods, two operators hand contoured and digitized the same irregularly-spaced subsurface elevations of the top of the Dundee Limestone. These two data sets were subjected to numerical analysis by each of the three methods. The resulting maps are shown in Figures 1-3.

It is evident in Figures 1 and 2 that for the orders computed the polynomial and Fourier Series models of this particular stratigraphic unit are not significantly affected by the differing data sets. The similarity of the mathematically derived trends appears to be such that operator bias should have little influence on the conclusions drawn from the maps generated by either method. The bias is reflected in the residual values.

There are, as expected some apparent differences in the filtered maps computed from the two sets of interpolated data (Fig. 3). In the western portion of the map area there is a dissimilarity in structural grain which could be significant to particular geological conclusions concerning the Dundee Limestone. The filter, in this instance, was designed to emphasize a size range of structures which are prominent petroleum reservoirs in this area of the Michigan Basin.

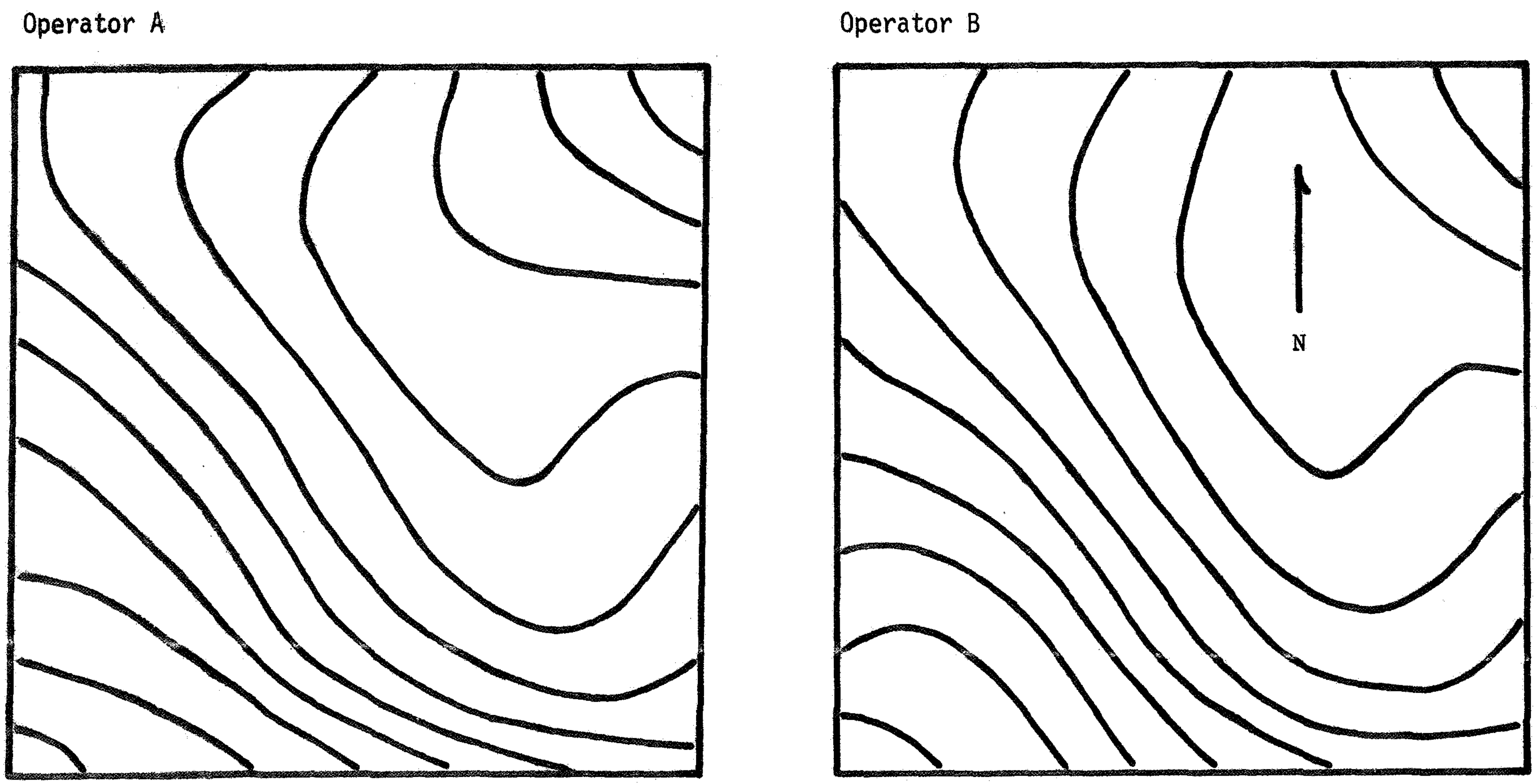

Figure 1.- Form of degree 8 polynomial trend surfaces of top of Dundee Limestone in subsurface of portion of Michigan Basin. Computed from interpolated data of two operators using the same irregularly spaced original data.

Operator A Operator B

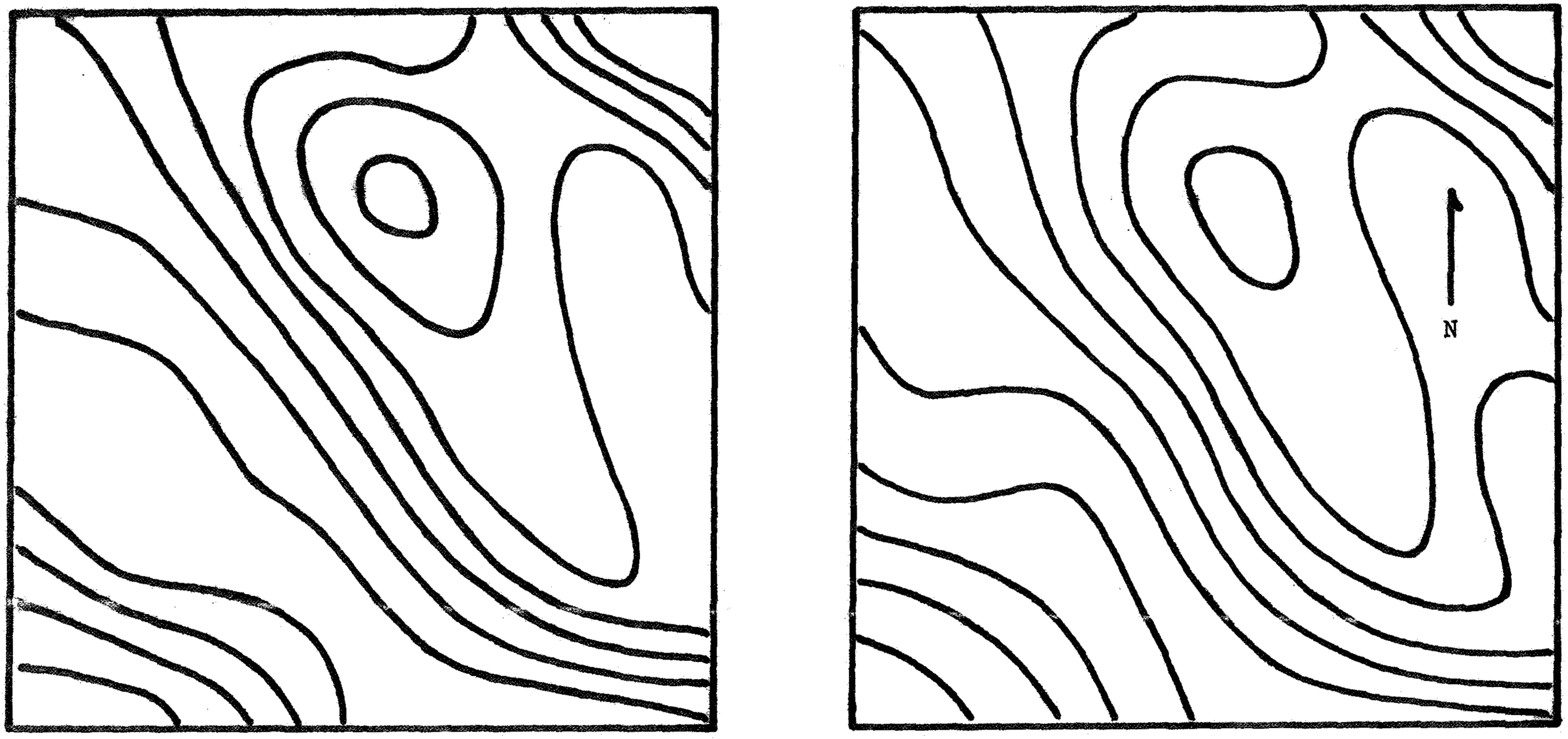

Figure 2.- Form of complete 3rd harmonic Fourier series trend surfaces of top of Dundee Limestone in subsurface of portion of Michigan Basin. Computed from interpolated data of two operators using the same irregularly spaced original data.

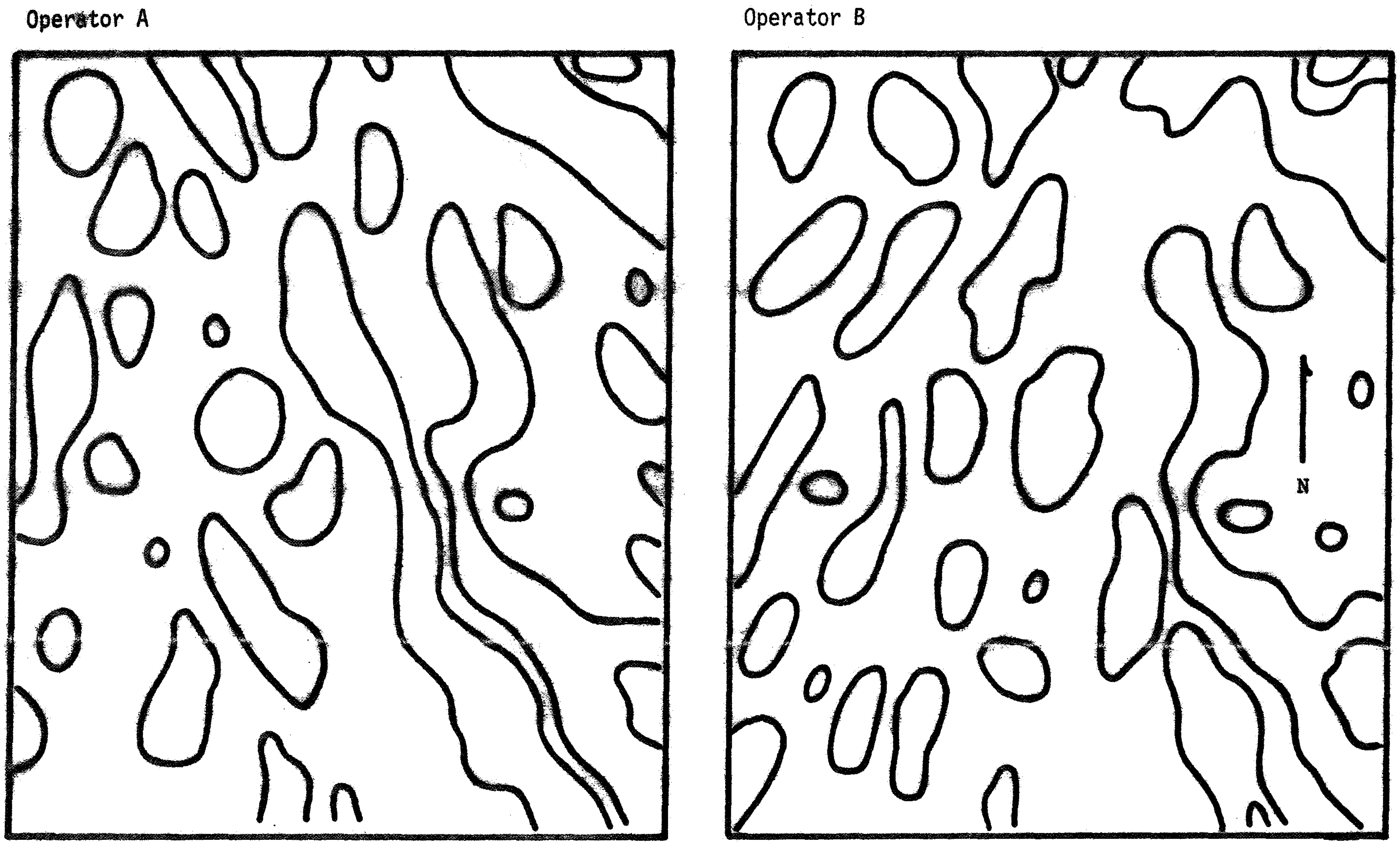

Figure 3.- Form of the filtered structural contours on top of Dundee Limestone in subsurface of portion of Michigan Basin. 11 x 11 filter used. Positive and negative structures with relief greater than 45 feet are shown. Computed from interpolated data of two operators using the same irregularly spaced original data.

For this particular study the original subsurface data density is such that it would appear improbable that different operators could generate completely different structural trends over the map area using manual contours without violating the data. It seems likely, however, that with more sparsely distributed, irregularly-spaced data, subjective bias introduced by manual contouring and interpolation could be a serious problem. It is difficult to justify the use of rigorous numerical methods for the analysis of data obtained in a substantially less-than-objective manner. It would seem more satisfactory in this situation if numerical methods would be used to obtain gridded data. Operator interpretation should be minimized until the completion of the numerical manipulations.

An investigation is being made of spline interpolation (Price and Simonsen, 1963; Bhattacharyya, 1969) as a more-rigorous method for obtaining gridded data. With the use of such a procedure, spatial filtering in all probability will be a more-effective tool for the analysis of geological data. It may prove to be of particular value in analyzing data for remote-sensing purposes as well as for the routine work of the exploration geologist and geophysicist.

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